A New View of the Universe

With Livermore's laser guide star and adaptive optics systems, the heavens are becoming clearer. Dim objects will become brighter, and some invisible ones will be visible.

ASTRONOMERS consider Earth's atmosphere a real nuisance. The very air we breathe distorts their view of the heavens and prevents a telescope from forming sharp images. But in recent years, scientists have found a way around this problem by using optical systems that correct incoming light, in effect getting rid of the turbulence in the atmosphere.

Known as adaptive optics, these systems for sensing and correcting atmospheric aberrations were first proposed in 1953. The first solution to be implemented was tilt-tip correction, the tilting of a secondary mirror several times a second to eliminate or reduce the dancing motion of an image. But that did not get rid of the blurring that the atmosphere produces. Sharpening the image required new technologies to split the incoming light beam into many small elements and correct each element separately, hundreds of times a second.

These technologies are available today because of research funded by the Departments of Energy and Defense into methods for imaging objects that are far away and for keeping a laser beam sharply focused in the atmosphere.

Right now, there are about 10 adaptive optics systems installed on astronomical telescopes. Adaptive optics correct incoming light from distant celestial bodies, which typically are very dim, by using a relatively bright, natural guide star as a reference. With adaptive optics, resolution of the dim objects improves dramatically—as long as they are close enough to a bright reference star.

When observing at visible wavelengths, astronomers using adaptive optics require a nearby fifth-magnitude star, one that is just bright enough to be seen unaided, as a natural guide star. For near-infrared observations, only a twelfth-magnitude star—a thousand times fainter—is needed. There are hundreds of thousands of these natural guide stars, but they are only enough to allow adaptive optics to function over about 1 percent of the sky.

Enter Lawrence Livermore's laser guide star and adaptive optics systems.

They can be mounted on a telescope and directed into virtually any part of the heavens an astronomer wants to study. In 1995, Livermore installed a laser guide star on the 3-meter Shane telescope at the University of California's Lick Observatory on Mount Hamilton near San Jose, California. The Shane became the first major astronomical telescope to use an artificial guide star system with full adaptive optics.

Every telescope has a limit to its resolution, defined largely by the size of the telescope's mirror. With Livermore's laser guide star and adaptive optics, the images obtained from the Shane telescope are as close to perfect as possible. The telescope can now achieve diffraction-limited results, meaning that only diffraction effects limit its performance. Figure 1 demonstrates how adaptive optics is improving astronomical viewing for near-infrared light.

Physicist Scot Olivier, who is leading the adaptive optics work at Livermore, is clearly excited about the work. "Results to date at Lick are impressive, and now an adaptive optics system is also being installed at the Keck II telescope in Hawaii. The two Keck telescopes are the largest in the world and are quickly becoming the preeminent tools in astronomy" (Figure 2).

The Lick Observatory system was the prototype for the one at the 10-meter Keck II telescope atop Mauna Kea in Hawaii. The two Keck telescopes are owned jointly by the University of California, the California Institute of Technology, and the National Aeronautics and Space Administration. Livermore and Keck Observatory are collaborating on the installation of the adaptive optics system. Livermore is responsible for developing the laser and high-speed wavefront control systems, and Keck personnel are responsible for the optomechanical system, user interface, supervisory control, and project management. Testing is expected to be completed by this fall; fully functional adaptive optics should be available for scientific use in early 2000. A laser guide star system designed and built by Livermore will also be installed at Keck next year.

A Sodium Star Is Born

Since the 1980s, two types of laser guide stars have been developed at laboratories and universities around the world. One uses Rayleigh scattering of ultraviolet or visible light at a height of 5 to 15 kilometers in the atmosphere. The other uses resonant scattering of light from a layer of sodium atoms that sits in the upper mesosphere at about 90 to 100 kilometers in altitude. The second scheme has the advantage of putting the reference beacon higher, thus sampling a larger portion of the path of light from a celestial object in space to a telescope on Earth.

The sodium guide star was an idea co-developed by Claire Max, currently Livermore's Director of University Relations, as part of a study for the Department of Defense in 1984. Max initiated Livermore work on laser guide stars and astronomical systems in the early 1990s, once laser technology had evolved to make these projects technically feasible. Engineer Herb Friedman led the development of the laser systems used in this work.

Livermore's guide star is created by a dye laser system, a cousin to the laser used for Livermore's Atomic Vapor Laser Isotope Separation (AVLIS) program. Green light from flashlamp-pumped, solid-state lasers beneath the main floor of the telescope dome travels through fiber-optic lines to a compact dye laser mounted on the side of the telescope. The dye laser converts

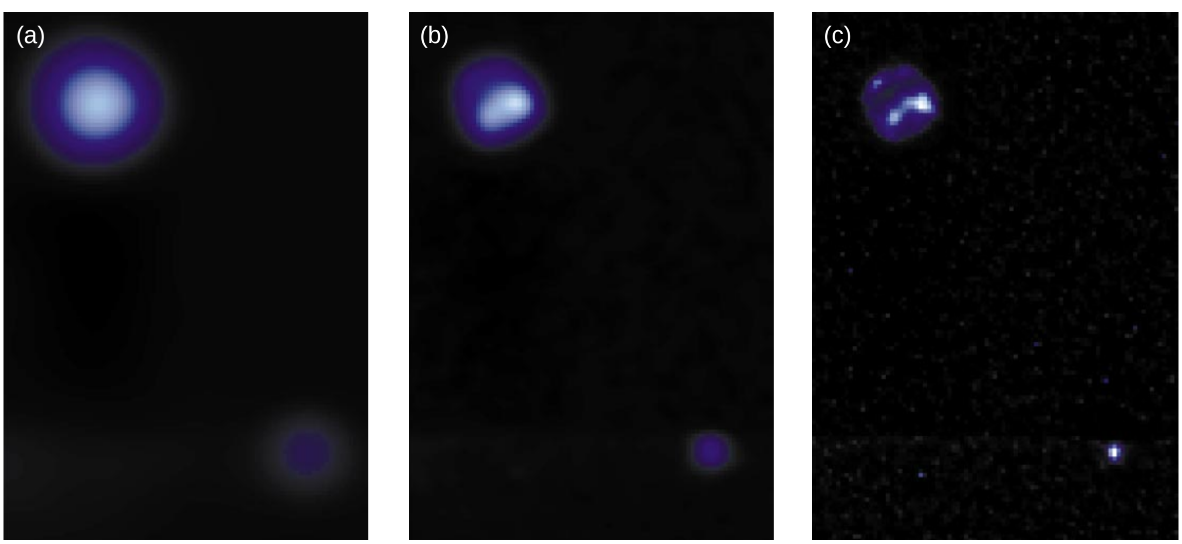
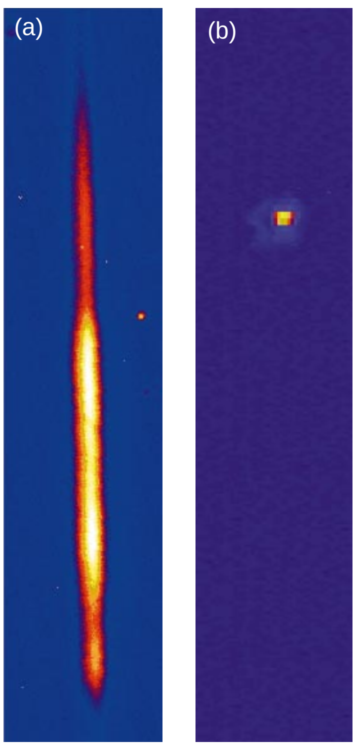


Figure 1. Three views of Neptune and its moon Triton: (a) a typical infrared image, (b) a better image taken from a better observation site, and (c) an image taken with adaptive optics, in which cloud bands are clearly visible. (Neptune and Triton are bright enough that a laser guide star is not needed to view them.)

Figure 2. Keck I and Keck II telescopes atop the Mauna Kea volcano in Hawaii.



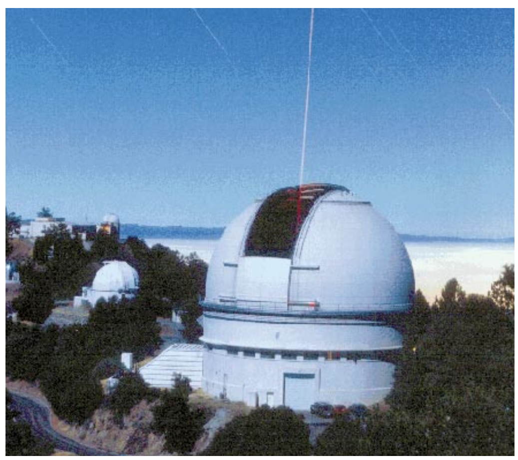


Figure 3. Views of the laser guide star at the Lick Observatory. (a) From another telescope at Lick, the guide star appears as a streak. (b) From the Shane telescope, the guide star looks like another star in the sky.

the light from green to yellow, the same color as sodium-vapor street lights. A beam projector then directs the yellow light up through the atmosphere.

For the first 30 or so kilometers, the light is visible because it is scattered by air molecules and dust in the atmosphere. For the next 60 kilometers, the light is invisible as it travels through the clearer stratosphere. Then at about 95 kilometers, the laser beam hits the layer of sodium atoms, the product of micrometeorites vaporizing as they enter the upper atmosphere. Tuned to 589 nanometers, sodium's resonant wavelength, the laser excites the atomic sodium, which emits the yellow light in all directions to create a glowing guide star (Figure 3).

As with any light source in the heavens, some of the light from this artificial sodium star travels back through the atmosphere. At the telescope, the adaptive optics system measures and corrects the guide star image for atmospheric distortions caused by air turbulence and temperature changes. Any corrections made to the guide star's light affect all of the celestial objects in the same patch of sky, thus improving the view of the particular object the astronomer wants to see.

Several research institutions around the world have carried out sodium guide star experiments, but the only other sodium laser guide star currently in use is at the Calar Alto Observatory in Spain. Its laser is about one-fifth as powerful as the one that Livermore is using at the Lick Observatory.

Covering the Sky

A natural guide star travels through Earth's atmosphere only once, while the laser guide star must traverse it twice, up and back. Atmospheric effects cause the artificial guide star to appear larger than a comparable natural guide star, making it somewhat less accurate as a reference point. A natural guide star is about two times more effective as a wavefront reference than the laser guide star, although engineer Don Gavel and others at Livermore are working to make the laser spot smaller to improve its performance.

But the laser guide star makes up for its deficiencies by offering a significant improvement in sky coverage. This is because the laser can be pointed anywhere in the sky to make a bright artificial star.

Making Stars Bright

In the adaptive optics system, a wavefront sensor and a deformable mirror make corrections to light beaming into the telescope (Figure 4). The system must work quickly because the atmosphere between the telescope and the heavens typically blows by at about 10 meters per second, requiring a correction every few milliseconds.

A tilt-tip mirror, with its own sensor and camera, makes the initial correction to the incoming beam of light to stop it from dancing. Then the beam travels to a deformable mirror where the shape of the incoming wavefront is determined. A Shack–Hartmann wavefront sensor, which at Lick has 40 subapertures, examines part of the shape of the incoming wavefront. The sensor measures the difference between the actual shape and a perfect, flat wavefront. The measurements go into a computer that directs the activities of the deformable mirror. As the atmosphere blows by, the wavefront sensor and deformable mirror are in constant communication, searching for errors and correcting them.

The mirror at Lick has 127 electrostrictive actuators—each a tiny piston—arranged in a triangular pattern. Each actuator can raise or lower a part of the mirror surface by as much as 4 micrometers to straighten out the incoming light and make it all travel in the same direction. (This mirror is much like other deformable mirrors that Livermore has developed to correct wavefront aberrations in laser light in the 192-beam National Ignition Facility.)

The goal for astronomical adaptive optics is to flatten the guide star's incoming wavefront to achieve as perfect and hence as bright an image as possible. Once the system operators are satisfied with the image they have achieved for the guide star, the imaging camera, also known as the science camera, is turned on to gather data on the celestial object of interest.

Keck has a larger adaptive optics system than Lick because its telescopes are much larger. At Keck, the wavefront sensor has 241 subapertures and the deformable mirror has 349 actuators arranged in a square pattern.

The View from Lick

With the laser guide star and adaptive optics mounted on Lick's Shane telescope (Figure 5), images of distant stars are smaller by a factor of almost 4. Figure 6 compares the view of a distant, dim star without adaptive optics in place and with laser guide star adaptive optics. This star is located in a part of the heavens where no bright natural guide star exists, so Livermore's laser system is the only method available for improving images.

Livermore scientists have used Lick's adaptive optics to examine young stars to see whether they are actually binary stars (Figure 7). Disks of dust within which planets are forming may surround some of these bright stars. Some scientists believe that our solar system was formed that way, and a look at a similar solar system in the making would be exciting indeed.

Livermore astronomer Bruce Macintosh has scheduled five nights in

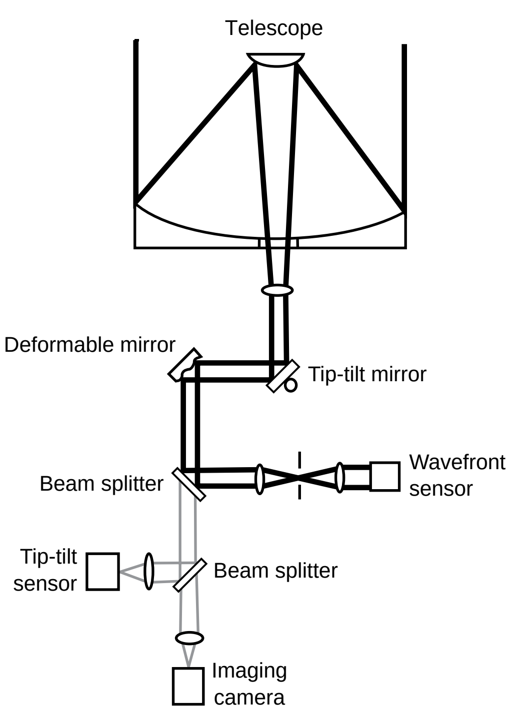


Figure 4. Schematic of adaptive optics system.

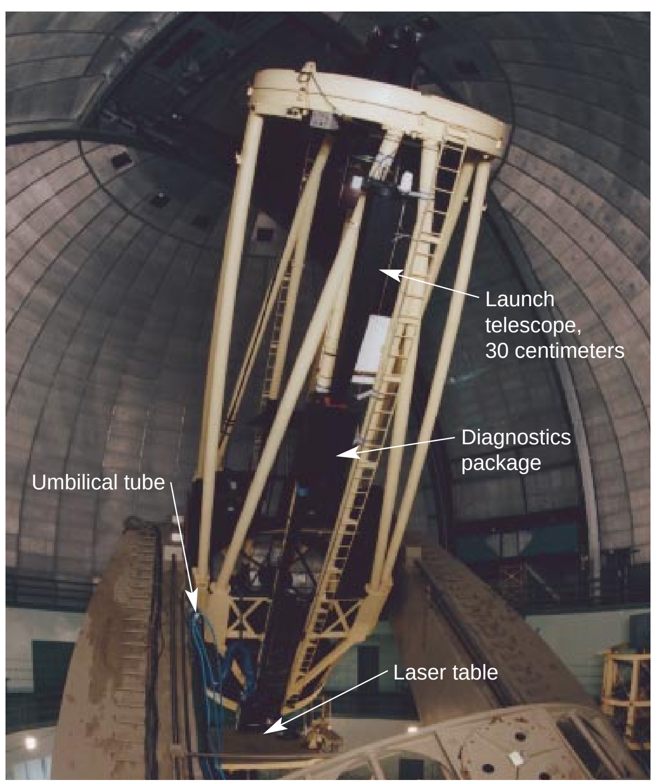


Figure 5. The Shane telescope at the Lick Observatory is mounted with the Livermore laser guide star and adaptive optics system.

September on the Shane telescope to search for nearby brown dwarf stars. Brown dwarfs have a mass between that of a large planet and a small star, as much as 80 times the mass of Jupiter. Their mass is too small to sustain fusion, but they still glow from stored heat. Brown dwarfs are thought to be a contributor to the dark matter in the universe. According to Macintosh, "Brown dwarfs are rare, so it takes a long time to search for them. Five nights in a row will be enough to look at all the young, nearby stars in half the sky. I have another five nights reserved in the spring of 2000 to look at the other half. All told, we will look at about 200 of the closest stars to see if any of them are brown dwarfs."

And the View from Keck

With the largest mirrors in the world, the Keck telescopes on Mauna Kea can produce the highest-resolution images available. With that capability, it is not surprising that demand is high for time at Keck. Even without an adaptive optics system, Keck's huge telescopes are bringing understanding to faint objects that until now have been difficult to see.

Saturn's moon Titan holds special interest for scientists because it is the only planetary moon that has a thick, nitrogen-dominated atmosphere. Although it is several hundreds of degrees colder than Earth and its atmosphere is rich in methane, in some ways its chemistry seems to be like that of Earth before life appeared. Titan's organic chemistry is also driven by sunlight, as Earth's is. On Titan, however, sunlight works to transform methane to ethane. Some scientists believe that Titan may have liquid seas formed by ethane that has "rained out" to produce reservoirs of liquid hydrocarbons. Titan's orange haze makes it impossible for Earth-bound scientists to see its surface in visible light, but in the near infrared, a few spectral "windows" allow surface features such as continents and potential hydrocarbon "oceans" to be detected.

Macintosh, scientist Seran Gibbard, and their colleagues from Livermore have been working at Keck with University of California–Berkeley professor Imke de Pater and her students to use speckle imaging to study Titan. With adaptive optics installed at only a few telescopes, speckle imaging has been the best way to learn more about many celestial objects. Traditional astronomical imaging uses long exposure times to gather as much light as possible and often results in a picture resembling a fuzzy blob. Speckle imaging involves taking several hundred pictures with short exposure times—snapshots to freeze atmospheric turbulence—and then reconstructing an image that is generally much sharper than otherwise available. But the method only works with bright objects.

Speckle images of Titan at Keck achieved higher contrast and spatial resolution than any previous images, including those from the Hubble Space Telescope. But speckle imaging is slow

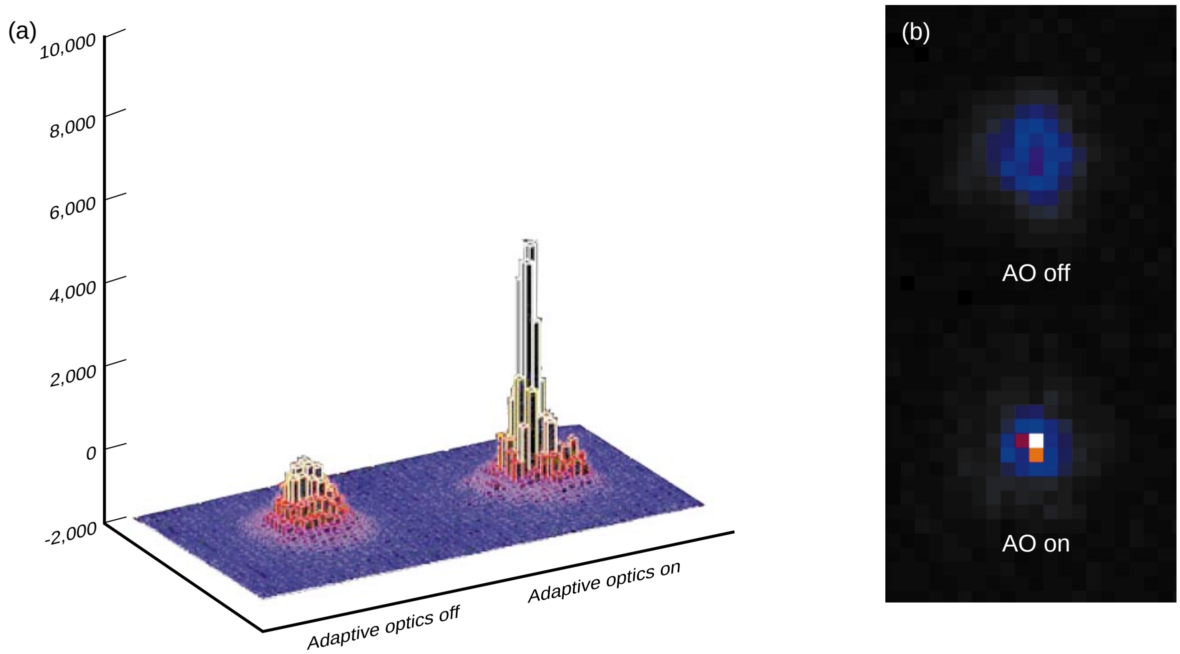


Figure 6. (a) Views of a star observed with and without laser guide star adaptive optics (AO) correction. (b) The AO correction makes the star smaller and its peak intensity brighter.

and inefficient. It requires taking many pictures, which means considerable time both on the telescope and on the computer to reconstruct a final image.

Recent tests of Keck's adaptive optics systems produced an even higher resolution image of Titan (Figure 8). Adaptive optics is much faster than speckle imaging, producing almost immediate results as well as better information about Titan's atmosphere and surface.

At Keck, Livermore astronomers also want to study binaries and other bright objects that do not need an artificial guide star. These include Neptune and Io, the innermost of Jupiter's moons. Io is the most volcanically active area in our solar system because of extreme tidal forces caused by the gravitational effects of nearby Jupiter.

Other Life out There?

In two years or so, when both adaptive optics and a laser guide star are available on the Keck II telescope, a whole new view of the universe will be possible. Once dim objects will look brighter, and some objects once invisible will become visible.

Just a few months ago, astronomers from San Francisco State University and Harvard made news yet again for discovering a star with a planetary system. This one appears to have three huge planets, the third and largest being four or more times the size of Jupiter. This marked the first discovery of another planetary system with more than two planets. Only the enormous mass of the third planet made it detectable.

Such discoveries come not from seeing the planets revolving around a star but from observing regular wobbles in the star's motion that result from the strong gravitational pull of nearby planets. Only very close and very large planets affect a star enough to induce the wobble. In fact, if

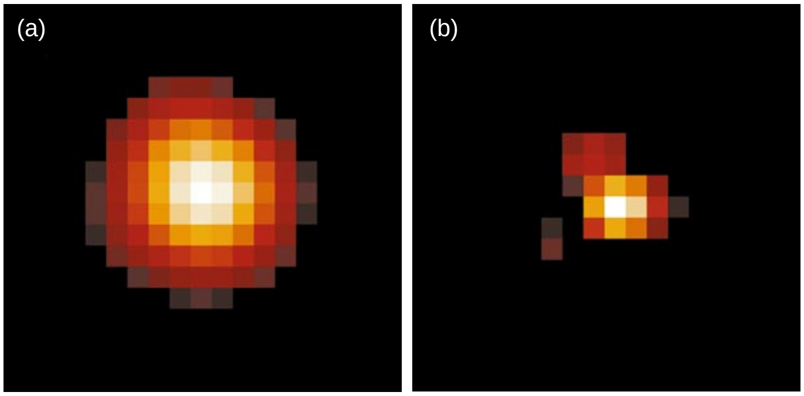


Figure 7. Images of FS Tau, a young star, (a) without adaptive optics and (b) with Lick laser guide star adaptive optics, in which a faint binary companion is seen.

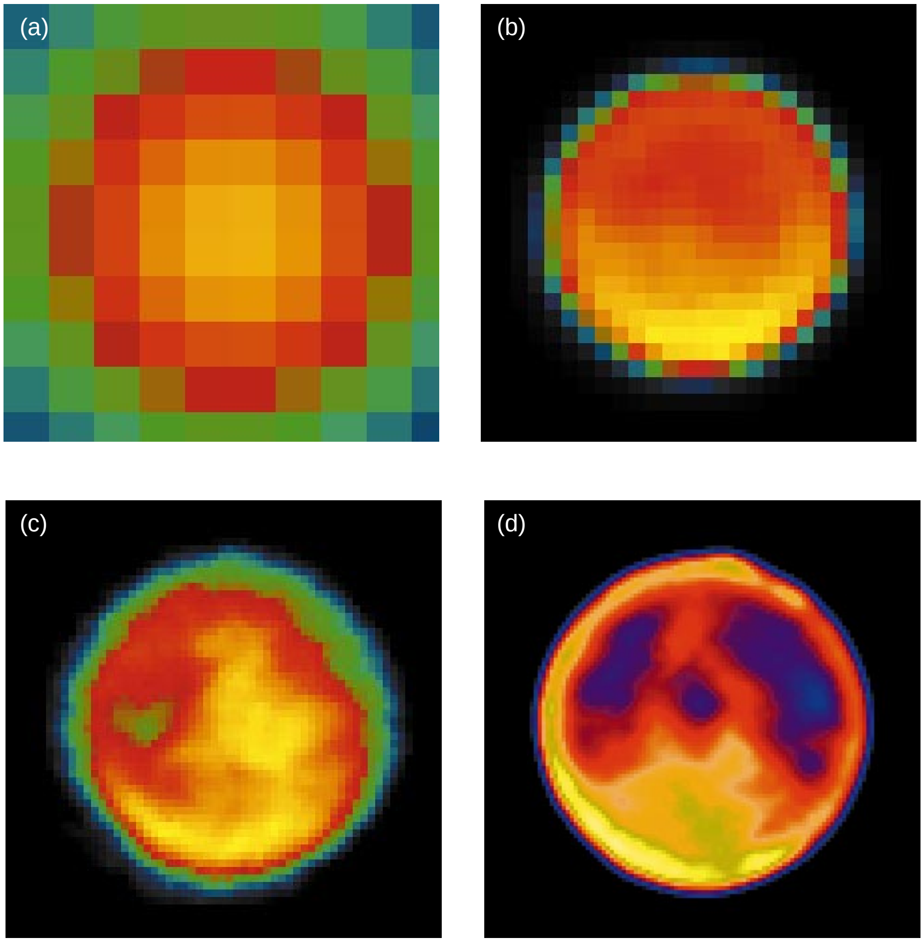


Figure 8. Four views of Titan obtained by different telescopes. (a) Image from a ground-based telescope without adaptive optics. (b) Image from the Hubble Space Telescope (diameter = 2.4 meters) at a wavelength of 0.8 micrometers. (c) Speckle image from the Keck 10-meter telescope in the near infrared. (d) Adaptive optics image from the Keck telescope in the near infrared, showing a different face of the moon than was imaged in (c).

Trainees from Hawaii at Livermore

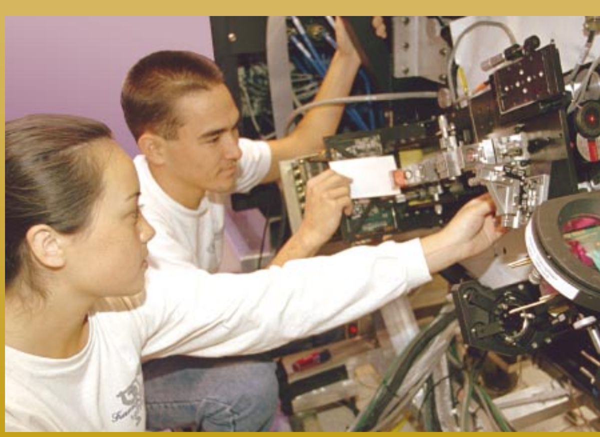
Livermore has been home since March to two interns from Hawaii who may some day work on the Keck telescopes or at one of the other great observatories in Hawaii. After completing general training in a variety of technical fields, Kristian `Alohalani Keahi from the island of Kaua`i and Shordon Kanaiaupuni Lopes from the island of Oahu began working in Livermore's adaptive optics laboratory. There they are operating lasers as well as setting up experiments and gathering data using a variety of optomechanical, electrooptical, and electromechanical equipment. They also have been working at the Lick Observatory as part of the Livermore team.

Their stay is part of Livermore's National Security Field Experience Initiative (NSFEI), which provides hands-on experience and mentoring to individuals interested in becoming part of the scientific and technological work force. NSFEI focuses on locations that are of strategic importance to national security, such as Hawaii and Alaska. The purpose of the internship program is to prepare the participants for careers in existing and emerging technologies, especially those that contribute to addressing global issues. The first NSFEI partnership was established in 1996 with ALU LIKE, Inc., a nonprofit, native Hawaiian training and job placement center.

Kristian and Shordon are two of eight Hawaiian interns who completed eight weeks of training at Livermore in late April. They worked in a variety of technical fields, such as computer system administration and applications, vacuum technology, electronics, telecommunications, machining, adaptive optics, and more.

"The interns are immersed in technology and given the big picture," says Marjorie Gonzalez, the NSFEI program leader. "Many started with an interest in telecommunications, but after being introduced to vacuum technology and optics, most chose to redirect their focus." Kristian and Shordon elected to gain more experience in adaptive optics.

After completing their training, NSFEI interns return to Hawaii where they seek entry-level employment, participate in additional on-the-job-training internships, or continue their formal education. All interns who have completed the program in the past are currently employed in Hawaii, several on defense-related environmental remediation projects and in defense telecommunications.



Kristian Keahi and Shordon Lopes in the adaptive optics laboratory.

someone on a planet somewhere else in the universe were observing our solar system with current detection techniques, the Earth and even Jupiter would not be detectable because the Earth is too small and Jupiter too far from the sun to impose much of a wobble.

The recently found planetary system may actually have more than three planets, but we cannot detect them yet. Astronomers hope that with adaptive optics, Keck will make that solar system or others like it not just detectable but actually visible in picturelike images.

Astronomers at Livermore also plan to study galaxies in the early universe to learn more about their structure. Located at the distant reaches of the universe, these dim galaxies require laser guide star adaptive optics to provide a clear view of the turbulent dynamic processes that led to their formation.

It's Not Over Yet

The success of the laser guide star and adaptive optics is enticing. If they work so well, what else can be added to give astronomers and astrophysicists even more information about the universe? Beginning next year, spectroscopic instruments will augment current adaptive optics imaging. Spectroscopy, long a part of the tool kit of those who study the sky, looks at the absorption and emission of light by matter. Each element gives off a different wavelength of light or signature spectrum.

Spectroscopic analysis has led to some remarkable astronomical discoveries. The study of spectral emissions of distant galaxies led to the revelation that the universe is expanding rapidly and in all directions. The finding was based on the observation of a Doppler shift of spectral lines. It was Edwin Hubble, after whom the Hubble Space Telescope is named, who discovered in the 1920s a roughly linear relationship between the distance of these galaxies from Earth and their Doppler shift. In any direction one looks, the farther away the galaxy appears, the faster it is receding from Earth.

Studying individual objects spectroscopically is more challenging than simply taking their pictures. Some objects in the sky are bright enough that scientists can apply spectroscopic analysis and determine their chemical makeup. But if the only image of an object is a poorly defined, faint blob, spectroscopic analysis is not always possible. Adaptive optics can solve that problem by replacing a blob with a much more clearly defined and brighter image. For example, we can now produce an image of Neptune clear enough for meaningful spectroscopic analysis of its clouds and its cloud-free regions (Figure 1c).

Research also continues on improving deformable mirrors. Work is under way on techniques that use liquid crystal and microelectromechanical devices to implement more phase control points. Thus far, Livermore has demonstrated a system with 1,800 liquid-crystal actuators. Mirrors as deformable as that could extend adaptive optics correction from near-infrared wavelengths into visible wavelengths for large astronomical telescopes.

As long as astronomers continue to study the skies from ground-based telescopes, our planet's atmosphere will be in the way. For us to be the living, breathing creatures we are, we wouldn't want it any other way. At least now there is a way to punch through the atmosphere and get a clear look at the entire sky.

—Katie Walter

Key Words: adaptive optics, astronomy, Keck Observatory, laser guide star, Lick Observatory.

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